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Luminous red mergers in the $z = 0.83$ cluster MS 1054–03: Direct evidence for hierarchical formation of massive early-type galaxies

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Abstract. We present results from a morphological study of the distant X-ray cluster MS 1054–03 at $z = 0.83$. We have obtained a large, two color HST WFPC2 mosaic of this cluster, and measured redshifts of 186 galaxies in the MS 1054–03 field with the 10m Keck telescope. Of 81 spectroscopically confirmed cluster galaxies observerd with HST, 13 are merger systems. Most of these mergers will likely evolve into luminous elliptical galaxies, and some may evolve into S0 galaxies. If the galaxy population in MS 1054–03 is typical for its redshift up to $\sim 50\,\%$ of ellipticals may have formed in mergers at $z < 1$. The mergers are generally red and have no detected [O II] 3727 Å emission. This result is consistent with the old stellar ages of ellipticals inferred from other studies. The mergers are preferentially found towards the outskirts of the cluster, indicating they probably occur in infalling clumps. A significant overabundance of close pairs of red galaxies detected in the outskirts of MS 1054–03 confirms the large number of interacting galaxies in this cluster.

1. Introduction

The formation epoch of early-type galaxies provides a strong test for galaxy formation models. Traditional models assume early-type galaxies formed in a

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"monolithic" collapse at very high redshift, followed by a smooth and regular dimming of the stellar light (e.g., Searle et al. 1973). In contrast, currently popular models for galaxy formation in CDM cosmologies predict that early-type galaxies were formed in many generations of mergers, and many ellipticals experienced their last major merger at $z < 1$ (e.g., Baugh, Cole, & Frenk 1996).

Early-type galaxies are easily studied in clusters, and most of what we have learned about the formation and evolution of early-types has come from studies of rich clusters at $0 < z < 1$ (e.g., Dressler et al. 1997). Strong constraints on the ages of the stars in early-type galaxies have come from studies of the evolution of the color-magnitude relation (e.g., Ellis et al. 1997, Stanford et al. 1998) and the Fundamental Plane (e.g., van Dokkum et al. 1998). These studies are all in remarkable agreement: most of the stars in early-type galaxies appear to have formed at high redshift ($z > 2$), and there is very little cluster-to-cluster scatter in their properties.

However, as pointed out by, e.g., Kauffmann (1996) the time of assembly of massive galaxies may be much more recent than the mean age of their stars. The FP and the CM relation do not provide constraints on the assembly time of early-type galaxies, unless some assumption is made regarding the amount of star formation during and prior to the mergers.

The relevance of merging can be constrained by other means. In particular, by studying large samples of distant galaxies the fraction of the galaxy population which is (at a given epoch) involved in a merger can be determined (e.g., Le Fevre et al. 1999). Here, we report on the merger fraction in the cluster MS 1054–03 at $z = 0.83$. We have obtained a large HST WFPC2 mosaic of the cluster, and combined this with extensive spectroscopy with the Keck telescope. The sample consists of 81 confirmed cluster members observed with HST. The results of this study are presented in full in van Dokkum et al. (1999).

2. Mergers in MS 1054–03

The most surprising result of our survey is the high fraction of galaxies classified as "merger/peculiar". We classified 17 % as mergers, compared to 22 % ellipticals, 22 % S0s, and 39 % spirals. Examples of the mergers are shown in Figure 1. We emphasize that all classified galaxies, including the mergers, are spectroscopically confirmed cluster galaxies.

The mergers are very luminous: the 13 mergers have a median luminosity $M_B^T \approx -22$ ($\sim 2L_*$ at $z = 0.83$), and five of the sixteen most luminous cluster galaxies were classified as mergers. The majority of the mergers will probably evolve into elliptical galaxies. The merger fraction in MS 1054 is comparable to the elliptical fraction: the number of ellipticals "in formation" is similar to the number of ellipticals already formed. Assuming the galaxy population in MS 1054–03 is typical for its redshift, this implies up to ~ 50 % of ellipticals formed in mergers at $z < 1$.

The high merger fraction in MS 1054–03 may seem surprising given the high velocity dispersion of the cluster ($\approx 1170\,\mathrm{km\,s^{-1}}$, Tran et al. 1999). The progenitors of the mergers must have had much lower relative velocities, indicating they were part of cold subclumps, which may in turn be merging with the cluster.

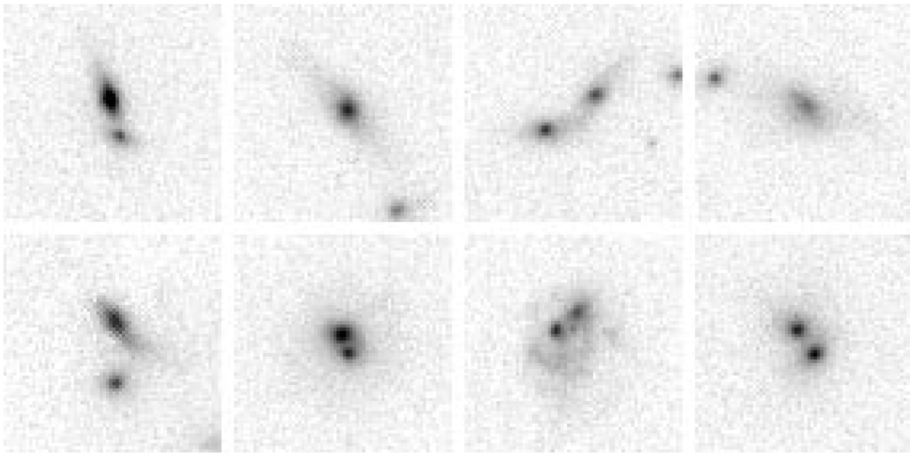

Figure 1. Examples of mergers in MS 1054–03 at $z = 0.83$. All galaxies are spectroscopically confirmed cluster members. These galaxies are among the most luminous in the cluster. Most of them will probably evolve into luminous ($\sim 2L_*$) ellipticals within ~ 1 Gyr.

The spatial distribution of the mergers supports this idea: they are preferentially located towards the outskirts of the cluster (see van Dokkum et al. 1999).

3. Close pairs

The merger fraction can be determined independently by examining the number of close pairs. Figure 2 shows the average galaxy density around red galaxies in our HST mosaic of MS 1054–03, excluding the central $400h_{50}^{-1}$ kpc of the cluster. The number of galaxies in each bin is weighted by the area; therefore, a flat distribution would show that the galaxies in the outer parts of the cluster are distributed uniformly.

There is a pronounced peak at separations $< 20h_{50}^{-1}$ kpc. This (preliminary) result confirms the large number of interacting galaxies in this cluster, and is completely independent from the morphological classifications.

4. Discussion

It may seem difficult to reconcile our results with the high formation redshifts inferred from studies of the luminosity and color evolution of early-type galaxies to $z = 1$ (e.g., Stanford et al. 1998, van Dokkum et al. 1998). However, this apparent conflict is at least partially solved by the observation that the merging galaxies in MS 1054–03 are red, and seem to have evolved stellar populations. Their colors indicate that the bulk of their stars was formed at $z > 1.7$ (see van Dokkum et al. 1999). The mergers are typically bulge dominated and have no detected [O II] 3727 Å emission; they appear to be mergers between E/S0s or early-type spirals. The available evidence suggests that the stars in massive early-types were formed at high redshift ($z > 2$), whereas the assembly of the

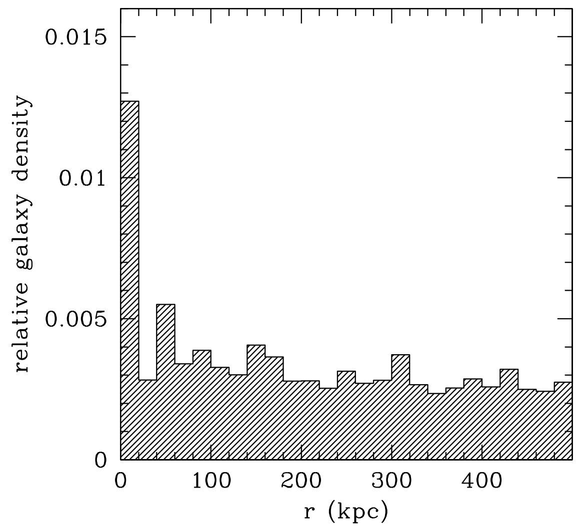

Figure 2. The average galaxy density around red galaxies in our HST mosaic of MS 1054–03, excluding the core of the cluster. There is a pronounced peak at separations $< 20h_{50}^{-1}$ kpc (or $2''$), demonstrating the presence of a large number of close pairs in the outskirts of MS 1054–03.

galaxies themselves continued to much lower redshift ($z < 1$). Our findings are strong evidence against galaxy formation in a monolithic collapse at high redshift, and in qualitative agreement with hierarchical galaxy formation models.

This study demonstrates that the combination of large field imaging with HST and deep spectroscopy from the ground can show directly how galaxy formation proceeded. The large field was essential, since the mergers are preferentially located in the outskirts of the cluster. Similar observations of high redshift clusters and the field would be valuable to test whether the results for MS 1054–03 are typical.

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